1 The internal-combustion engine: an introduction

1.1 Heat engines and internal combustion engines

It is appropriate to begin with a simple definition of the engine as a device for converting energy into useful work. The goal of any engine is to convert energy from some other form into "mechanical force and motion." The terms "mechanical force" and "motion" are chosen to convey the idea that the interest may be both in work output – how much force can be applied to move something a given distance – and in power output – how quickly the work can be done.

Turning attention to the energy that is being converted to do the desired work, our interest is in the chemical energy bound up in the molecular structure of a hydrocarbon fuel. Fundamental to any chemical reaction are the facts that it takes energy to break a chemical bond and that energy is released when new bonds are formed. If the energy released in forming new bonds is greater than that required to break the old bonds, the result is an **exothermic** reaction and net energy available to do work.

Fundamental to any combustion engine is the reaction of a hydrocarbon fuel with oxygen to form carbon dioxide and water. This combustion reaction is highly exothermic – a large amount of energy is released. The goal of the engine will be to utilize that energy repeatedly, efficiently, and cost-effectively. The next question with which the engine designer is faced is that of developing a mechanical device that accomplishes these objectives.

Beginning from this general discussion of combustion engines, one can now make distinctions between various types of engines. These distinctions may be based on thermodynamic process decisions, as well as on the mechanical hardware. The first distinction to be made is that between the **heat engine** and the **internal-combustion engine**, as shown in Fig. 1.1 – they really are two different things, although they have often been confused or incorrectly identified. By definition, a heat engine is an engine in which a working fluid undergoes various state changes through an operating cycle. The working fluid experiences a heat addition in which its pressure and temperature

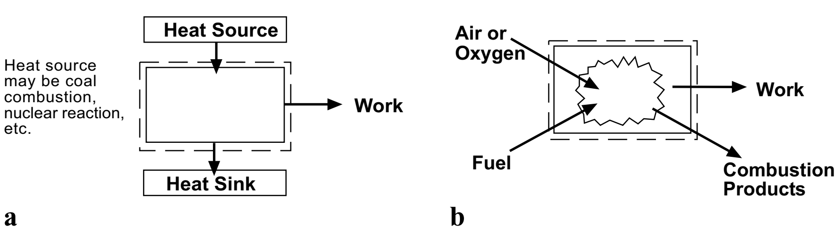


Fig. 1.1. Heat engine (**a**) and internal-combustion engine (**b**)

increase. It then goes through a process converting a portion of its energy to work. Cycle completion requires heat rejection from the fluid to the environment. A Rankine cycle steam turbine, using either coal combustion or a nuclear reaction to provide the heat source (and steam as the working fluid), is a practical example of a heat engine.

The "air standard" Otto cycle and diesel cycle are theoretical representations of processes similar to those of a spark-ignition or diesel engine, but they assume the working fluid to be air, gaining energy from an external source. In the actual diesel or spark-ignition engine, the energy release occurs within the system, and the working fluid undergoes not only a state change but a change in chemical composition. Another example of a practical internal-combustion engine is the gas turbine – not to be confused with the air standard Brayton cycle. The reader is referred to the recommended readings at the end of this chapter for a further discussion of the concepts introduced here.

Earlier it was emphasized that any practical engine will be expected to produce work repeatedly (or continuously over some period of time), efficiently, and cost-effectively. These terms have been carefully chosen to convey separate expectations – all of which must be met for an engine to be practical. The discussion begins with an emphasis on efficiency and cost-effectiveness; the need for continuous production of work will be taken up shortly. Efficiency is a commonly used engineering term, and the classic definition will suffice here. With this measure one can assess how well the energy available can be converted into useful work. Cost-effectiveness is a more difficult measure to accurately obtain and is less well understood by engineers. Nevertheless, it is every bit as important, and in many cases far more important, to a successful design. Listed below are the various elements defining the cost-effectiveness of an engine:

Development, production, and distribution costs
Maintenance costs
Fuel costs
Rebuild costs over useful life
Disposal costs of parts and fluids
Minus resale value at end of usage period

The elements listed together on the first line are ultimately reflected in the purchase price of the engine. As such, they provide the most direct measure of whether a given engine will be viable.

The remaining elements are tracked to a greater or lesser extent in particular markets. For example, while many automobile purchasers will consider only the purchase price (from this list) in making their buying decision, the company purchasing several hundred trucks or buses on which their company depends for its economic viability will almost certainly closely track every item on this list. The combination of these measures goes a long way in explaining why the internal combustion engine remains so difficult to replace.

Earlier the internal-combustion engine was defined in general terms. Various types of practical engines fit this definition; these types are distinguished by the combination of their combustion process and mechanical configuration. The combustion process may be continuous, as with the gas turbine engine, or intermittent, as with both the diesel and spark-ignition engines. A mechanical configuration must then be selected that meets the criteria of efficiency and cost-effectiveness, as well as allowing the work to be produced continuously. The idea is to create a mechanical arrangement that contains the combustion process and utilizes the high pressure and temperature of the combustion products to produce useful work.

1.2 The reciprocating piston engine

While many configurations have been proposed, patented, and demonstrated over the years, few have enjoyed commercial success. Such success results from the ability to address the combination of efficiency and cost-effectiveness discussed previously. In the remainder of this book the discussion will be limited to the reciprocating-piston engine. This engine is characterized by a slider–crank mechanism that converts the reciprocating, cyclic motion of a piston in a cylinder into the rotating motion of a crankshaft.

The primary components of the reciprocating engine are shown in Fig. 1.2. The moving piston controls the volume of the combustion chamber between a minimum at top dead center (TDC) and a maximum at bottom dead center (BDC). The ratio between the volume at BDC and that at TDC is referred to as the **compression ratio**. The change in volume is the **displacement** of the cylinder. The displacement of the cylinder multiplied by the number of cylinders is the displacement of the engine. The cylinder is sealed opposite from the moving piston by the cylinder head. In most engines the intake and exhaust valves are located in the cylinder head, as shown in Fig. 1.2.

The piston is linked to the crankshaft through a connecting rod. As the crankshaft spins about its centerline (the main bearing bore in the cylinder block), the offset of the rod bearing from the main bearing determines the travel of the piston. As the crankshaft rotates one half revolution from the position shown in Fig. 1.2, the piston moves from its TDC to its BDC position. The distance the piston travels is referred to as the **stroke** of the engine. The stroke is equal to twice the offset between the main bearing and rod bearing centerlines of the crankshaft. The diameter of the cylinder is referred to as its **bore**, and the combination of bore and stroke determines the displacement of the cylinder by the equation

$$\text{displacement} = \frac{\pi(\text{bore})^2(\text{stroke})}{4}$$

The crankshaft protrudes through the rear of the engine, where a flywheel and clutch pack or flex plate and torque converter are attached through which the load will be transmitted. Typically at the front of the engine, the crankshaft will drive the camshaft through a system of gears, a chain,

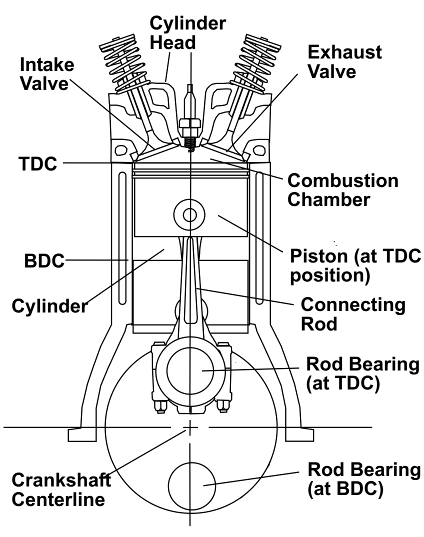


Fig. 1.2. Major operating components of the reciprocating-piston internal-combustion engine. TDC, top dead center; BDC, bottom dead center

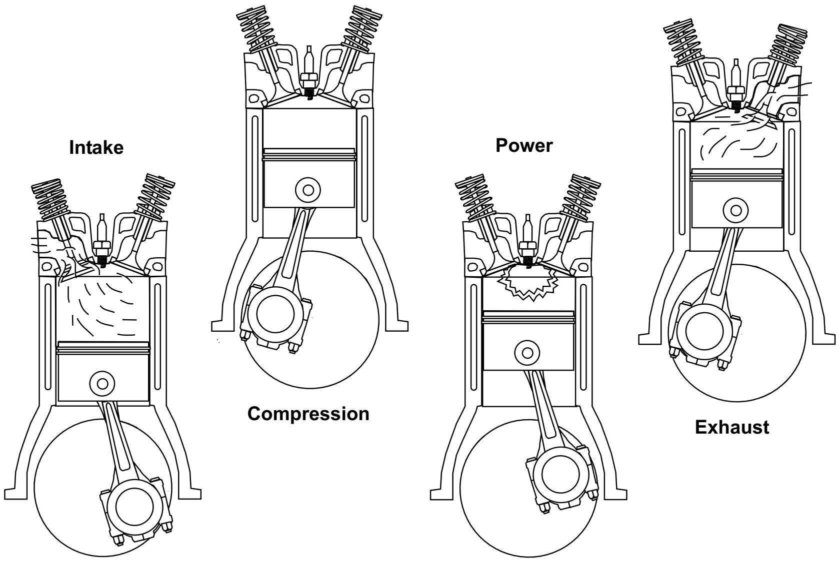


Fig. 1.3. Four-stroke operating cycle shown for a spark-ignition engine

or a cogged belt. The intake and exhaust valves are then actuated by the camshaft(s), either directly or through a valve train. Various support systems for cooling and lubricating the engine and for supplying the fuel and igniting the mixture are also required.

Each of the components and subsystems with the exception of the fuel and ignition systems will be discussed in detail in the remaining chapters of this book. Because of the variety of fuel and ignition systems, and the availability of previously published books devoted to these systems, they will not be covered in this book.

1.3 Engine operating cycles

Having introduced a particular mechanical mechanism designed to repeatedly extract useful work from the high temperature and pressure associated with the energy release of combustion, we are now ready to look at the specific processes required to complete this task. Figure 1.3 shows the four-stroke operating cycle, which, as the name implies, requires four strokes of the piston (two complete revolutions of the crankshaft) for the completion of one cycle.

In the spark-ignition engine shown, a “charge” of premixed air and fuel is drawn into the cylinder through the intake valve during the intake stroke. The valve is then closed and the mixture compressed during the compression stroke. As the piston approaches TDC, a high-energy electrical spark provides the activation energy necessary to initiate the combustion process, forcing the piston down on its power stroke. As the piston nears BDC, the exhaust valve opens, and the spent combustion products are forced out of the cylinder during the exhaust stroke. The work output is controlled by a throttle restricting the amount of air–fuel mixture that can pass through the intake valve.

A four-stroke **diesel** engine operating cycle would consist of the same processes. However, air alone would be drawn into the engine and compressed. The spark plug would be replaced with a fuel injector spraying the fuel directly into the cylinder near the end of the compression process. The activation energy would be provided by the high temperature and pressure of the air into which the fuel is injected. The work output would be controlled by the amount of fuel injected.

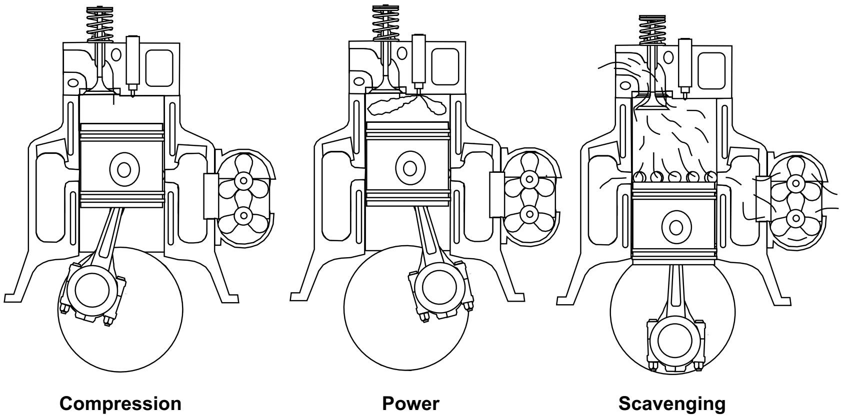


Fig. 1.4. Two-stroke operating cycle shown for a heavy-duty diesel engine

An alternative to the four-stroke cycle is the two-stroke cycle shown in Fig. 1.4. As implied, a complete operating cycle is achieved with every two strokes of the piston (one revolution of the crankshaft). The compression and power strokes are similar to those of the four-stroke engine; however, the gas exchange occurs as the piston approaches BDC, in what is termed the **scavenging** process. During scavenging the intake and exhaust passages are simultaneously open, and the engine relies on an intake supply pressure maintained higher than the exhaust pressure to force the spent products out and fill the cylinder with fresh air or air–fuel mixture.

The engine shown in Fig. 1.4 is a heavy-duty two-stroke diesel. The incoming air is pressurized with a crankshaft-driven compressor, and enters through ports near the bottom of the cylinder. In this engine, exhaust valves similar to those of the four-stroke engine are mounted in the cylinder head. Light-duty two-stroke engines are often crankcase supercharged. In such engines, each time the piston moves upward in the cylinder, a fresh charge (mixed with lubricating oil) is drawn into the crankcase. As the piston moves down, the crankcase is sealed and the mixture is compressed – the mixture is then transferred from the crankcase through the intake ports as the piston approaches BDC. This configuration is shown in Fig. 1.5.

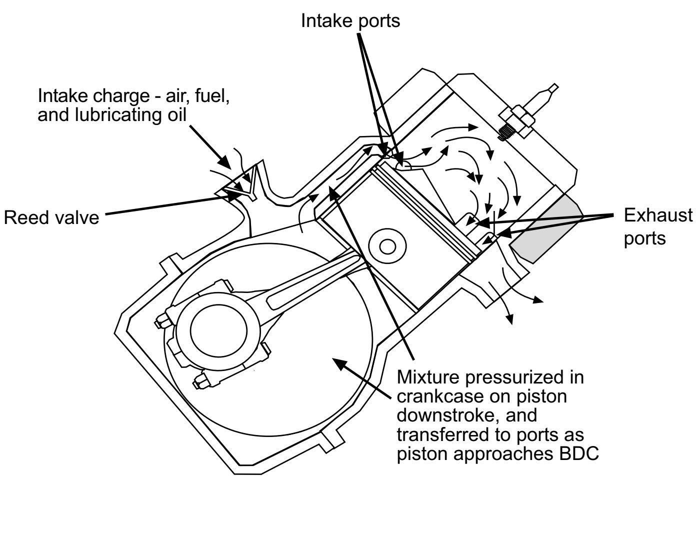


Fig. 1.5. Light-duty two-stroke engine

In the spark-ignition configuration, the engine suffers the disadvantage of sending fresh air–fuel mixture out with the exhaust during each scavenging period. Much recent attention is being given to engines that overcome this problem by injecting the fuel directly into the cylinder after the ports have been sealed.

1.4 Supercharging and turbocharging

In order to increase the specific power output of an engine (power output per unit of displacement), some form of precompression is often considered. This is rapidly becoming standard practice in diesel engines and is often seen in high-performance spark-ignition engines.

The engine that draws fresh charge into the cylinder at atmospheric pressure and exhausts directly to the atmosphere is termed naturally aspirated. As was shown in Fig. 1.4, a crankshaft-driven compressor may be added to elevate the pressure of the air (or mixture) prior to drawing it into the cylinder. This allows more mixture to be burned in a given cylinder volume. The crankshaft-driven device is generally referred to as a supercharger (although this general term is sometimes used to describe a turbocharger as well).

Recognizing that the exhaust gases leaving the engine still contain a significant quantity of energy that was not recovered as work, an alternative is to use a portion of this energy to drive the compressor. This configuration is the turbocharged engine.

Whenever the air is compressed, its temperature increases. Its density can be further increased (and still more air forced into the cylinder) if it is cooled after compression. The **charge air cooler**, variously termed intercooler (cooling between stages of compression) and aftercooler (cooling after compression), may be used with either the turbocharger or supercharger.

1.5 Production engine examples

For automobile engines, cost, weight, and package size are important design parameters in addition to the customer expectations regarding performance and fuel consumption. In most applications, the duty cycle is quite light, with the full power output utilized for only a small fraction of the engine's operating time. Engines in these applications will have from three to twelve cylinders, with the majority having between four and eight. The in-line and vee configurations are most common, with horizontally opposed and "W" configurations sometimes seen. Spark-ignition examples are depicted in front and side view section drawings in Fig. 1.6 a–c. Those shown in Fig. 1.6 a and b are both double-overhead-cam (DOHC) in-line four-cylinder engines. The engine shown in Fig. 1.6 c is a high-performance, DOHC V-8 incorporating a variable-length intake runner system, and variable valve timing and valve event phasing. A series of photos of a DOHC V-6 engine is presented in Fig. 1.7 a–d.

Of resurgent interest in automobile applications worldwide is the diesel engine, examples of which are shown in Fig. 1.8 a and b. The new diesel engines are universally turbocharged as this has allowed displacements comparable to those of their spark-ignition counterparts. The primary attraction of the diesel engine in automobile applications is its significantly higher inherent fuel economy. Greater reliability and durability are further attractions. These must be offset against higher initial cost, the challenges of meeting exhaust emission regulations, noise, and cold-weather startability.

Heavy-duty engines as referred to in this book are those used for trucks and buses. In many cases the same engines, or engines of very similar design, are used in agricultural and construction equipment, as well as various marine, industrial, and stand-by power applications. These further

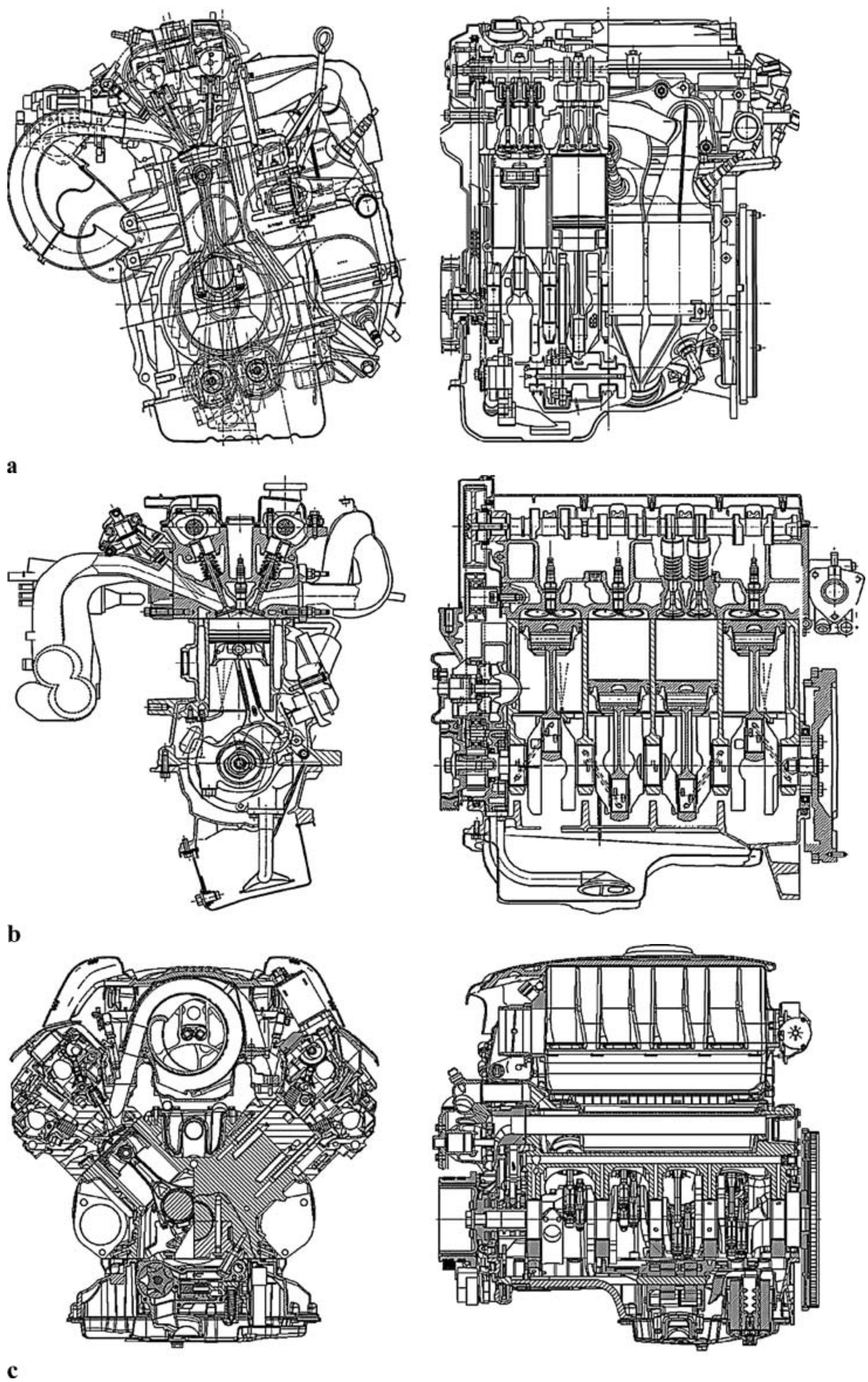


Fig. 1.6. **a** Four-cylinder, double-overhead-cam spark-ignition automobile engine (courtesy of Toyota Motor Company). **b** Four-cylinder, double-overhead-cam spark-ignition automobile engine (courtesy of Ford Motor Company). **c** Double-overhead-cam, high-performance V-8 engine (courtesy of BMW GmbH)

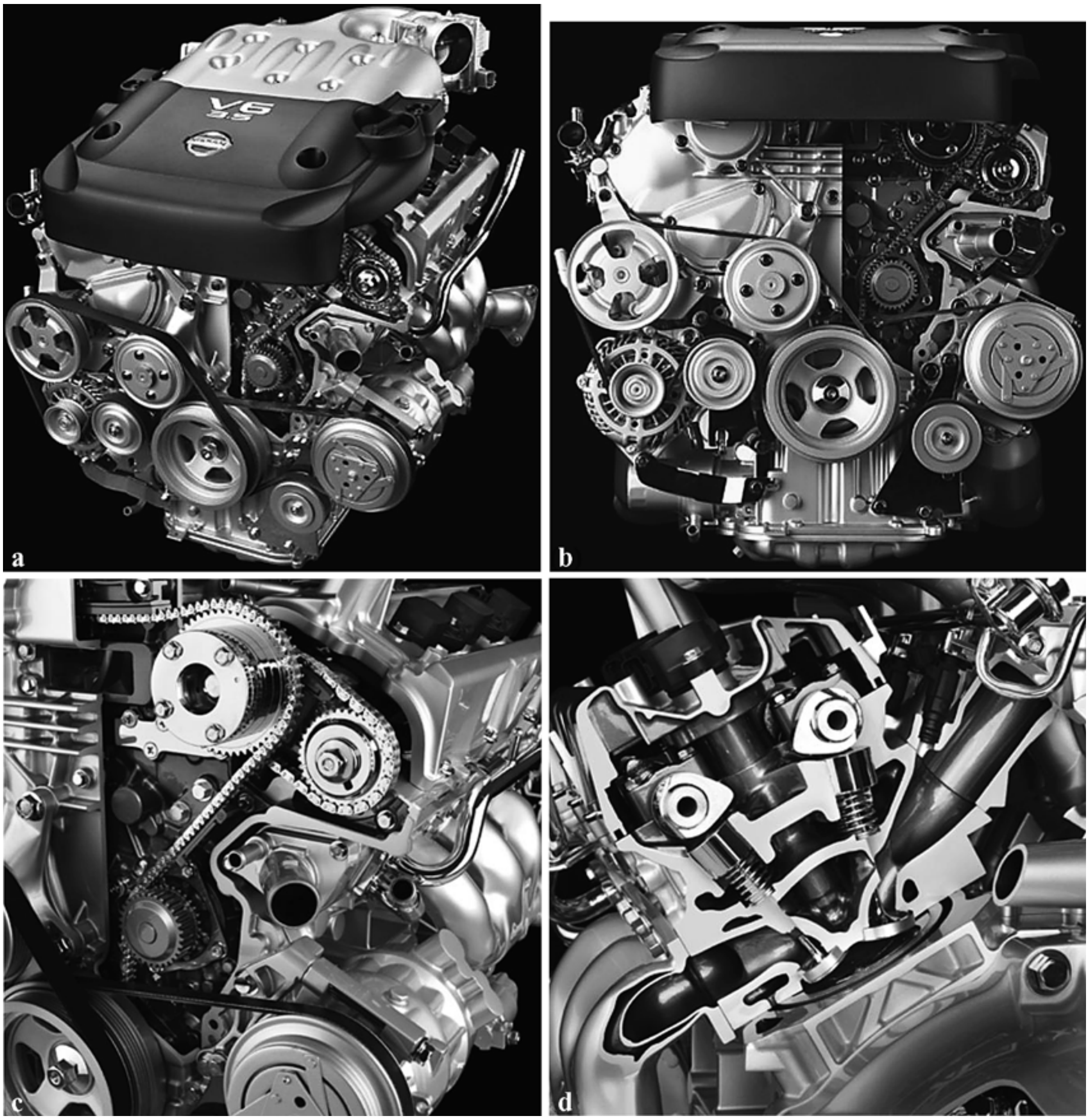
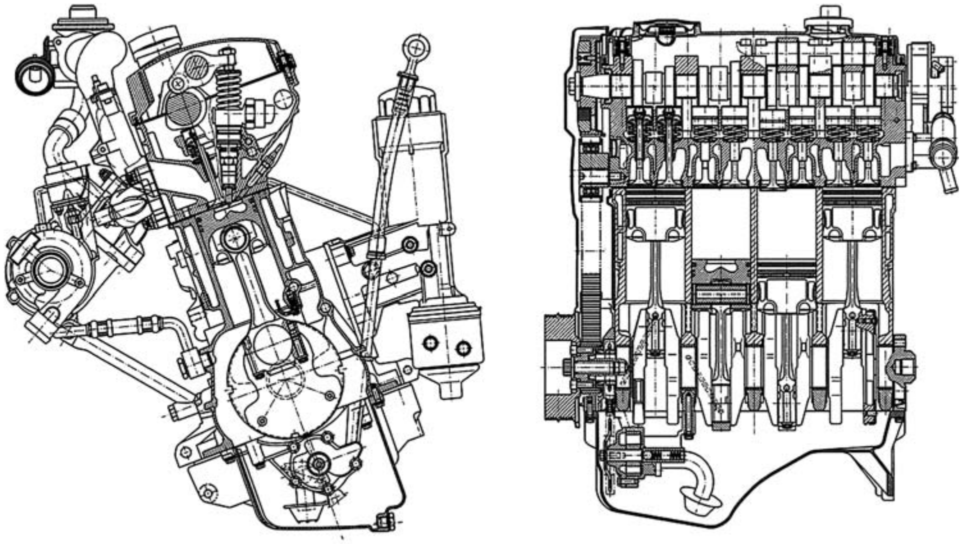
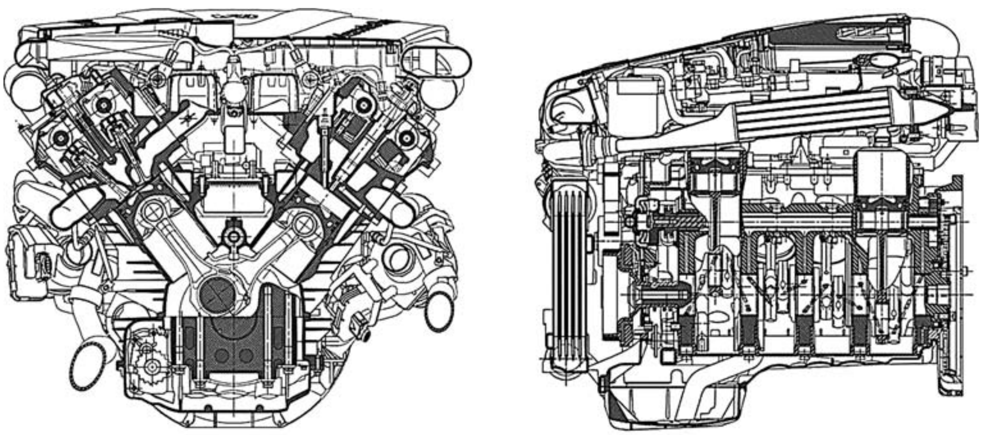


Fig. 1.7. a–d. Double-overhead-cam V-6 engine. **a** Cut-away shows cam drive chain. **b** Front view showing serpentine belt accessory drives and cam drive cut-away. **c** Details of cam drive, showing variable-timing device for the intake camshaft. **d** Cylinder head, intake and exhaust manifold cut-away (courtesy of Nissan Motor Company)

applications will not be specifically addressed, but much of the engine design discussion will apply equally to these applications. Once the power and torque output requirements have been met, the single most important design criterion for many of these engines is that of durability under a highly loaded duty cycle. Cost, weight, and package size are again important, but within the bounds defined by the durability requirement. In other words, these engines are significantly larger, heavier, and more expensive than automobile engines, but these design criteria remain important relative to competitive engines for similar applications. New engines for heavy-duty applications in trucks and buses are almost universally in-line engines with from four to six cylinders. They are highly turbocharged diesel engines.



a



b

Fig. 1.8. a Four-cylinder, single-overhead-cam, direct-injection turbocharged diesel automobile engine (courtesy of Volkswagen Audi GmbH). **b** Double-overhead-cam V-8, direct-injection turbocharged diesel automobile engine (courtesy of Mercedes Benz GmbH)

While considerably more time could be spent discussing the engines shown in Figs. 1.6 to 1.8, such discussion is deferred until later in the book. The reader will be asked to refer back to these figures many times in the upcoming chapters as various components and subsystems are further described.

1.6 Basic measures

A detailed discussion of engine performance measures is beyond the scope of this book, but a brief review of the most commonly used measures will be necessary to the further discussion. The reader is referred to the recommended readings at the end of this chapter for a more complete presentation of these and other measures.

Torque and power

Fundamental to engine performance is the relationship between work and power. The work, or useful energy output of the engine, is generally referred to as the torque output. Of particular interest in most engine applications is not only how much work can be done but the rate at which it can be done. The power of the engine is the time rate at which work is done. This is simply the product of engine torque and shaft speed,

$$P = TN;$$

English:

$$P\,[\mathrm{bhp}] = T\,[\mathrm{ft\,lbf}] \cdot N\,[\mathrm{rpm}] \cdot \frac{1\,\mathrm{min}}{60\,\mathrm{s}} \cdot \frac{2\pi}{\mathrm{rev}} \cdot \frac{\mathrm{hp\,s}}{550\,\mathrm{ft\,lbf}} = \frac{T\,[\mathrm{ft\,lbf}] \cdot N\,[\mathrm{rpm}]}{5252}$$

Metric:

$$P\,[\mathrm{kW}] = T\,[\mathrm{N\,m}] \cdot N\,[\mathrm{rpm}] \cdot \frac{1\,\mathrm{min}}{60\,\mathrm{s}} \cdot \frac{2\pi}{\mathrm{rev}} \times 10^{-3} = T\,[\mathrm{N\,m}] \cdot N\,[\mathrm{rpm}] \cdot (0.1047 \times 10^{-3})$$

Mean effective pressure

There are two physical interpretations that can be used to define the mean effective pressure. First, it is the constant pressure acting over the same volume change (from TDC to BDC) that would produce the same work as the actual engine cycle. Note that since the pressure-volume analysis gives us the net indicated work, this interpretation provides the **indicated mean effective pressure**, or IMEP. The second interpretation is that mean effective pressure is the work output of the engine divided by its displacement. If indicated work is divided by engine displacement, the result is the IMEP. If however the brake work is divided by displacement, the result is the **brake mean effective pressure**, or BMEP. The calculation follows:

$$\mathrm{BMEP} = \frac{(\text{brake power}) \cdot (\text{rev/cycle})}{D \cdot N}$$

English:

$$\mathrm{BMEP}\,[\mathrm{psi}] = \frac{P\,[\mathrm{bhp}] \cdot (2\,\text{rev/cycle [if four-stroke]}) \cdot 396{,}000}{D\,[\mathrm{in}^3] \cdot N\,[\mathrm{rpm}]}$$

Metric:

$$\mathrm{BMEP}\,[\mathrm{kPa}] = \frac{P\,[\mathrm{kW}] \cdot (2\,\text{rev/cycle [if four-stroke]}) \cdot 10^3}{D\,[\mathrm{liter}] \cdot N\,[\mathrm{rev/s}]}$$

Specific fuel consumption

Another important measure of engine performance is its thermal efficiency – how efficiently the fuel energy is being converted into useful work. The measure of efficiency most commonly applied

to engines is the **specific fuel consumption**, or SFC. The specific fuel consumption is simply the mass flow rate of fuel divided by the power output. If brake power is used in the calculation, the result is the **brake specific fuel consumption**, or BSFC:

English:

$$\text{BSFC [lbm/(HP h)]} = \frac{\dot{m}_{\text{fuel}}\ [\text{lbm/h}]}{P\ [\text{bhp}]}$$

Metric:

$$\text{BSFC [g/(kW h)]} = \frac{\dot{m}_{\text{fuel}}\ [\text{g/h}]}{P\ [\text{kW}]}$$

Similarly, indicated power would be used to calculate **indicated specific fuel consumption**, or ISFC. It should be noted that if one knows the energy content per unit mass of the fuel, the thermal efficiency can be directly calculated by taking the inverse of the specific fuel consumption and multiplying the mass flow rate of the fuel by the energy per unit mass. The result of these operations is the rate at which work is done (power) divided by the rate at which fuel energy is supplied. The energy of the fuel is generally taken as its lower heating value at constant pressure.

Volumetric efficiency

The ability to produce work will always be limited by the ability to supply sufficient oxygen for the combustion process. Therefore, an important measure is that of how well the cylinder can be filled during each intake stroke. The measure used is volumetric efficiency. The name is a bit misleading as it is actually a mass ratio. It is the ratio of the actual mass flow rate of air into the engine divided by the ideal mass flow rate – that which would be supplied if the cylinder could be completely filled with air at the supply conditions:

$$\eta_{\text{vol}} = \frac{\dot{m}_{\text{actual}}}{\dot{m}_{\text{ideal}}} = \frac{\dot{m}_{\text{actual}}}{\rho_{\text{ref}}\, D \cdot N\ [\text{rpm}]/2\ \text{rev/cycle}}$$

Two important points must be noted. First, by convention, the mass flow rates used are that for the air alone. Even though the spark-ignition engine inducts a mixture of air and fuel, the mass of the fuel is not included. This is an important point as it will have a measurable impact on the result.

Second, one must always be clear on the reference conditions being used for the density calculation. For naturally aspirated engines, it is normal to use the density at ambient pressure and temperature. For supercharged or turbocharged engines, one may use ambient density (in which case the resulting volumetric efficiency will be well over 100 percent) or the density at the intake port pressure and temperature.

1.7 Recommendations for further reading

The study of thermodynamics underlying engine performance and efficiency was briefly introduced in this chapter, but the remainder of this book is devoted to the mechanical sciences as applied to engine design. For further reading on engine thermodynamics, performance, combustion, and emissions the reader is referred to the following text by John Heywood. This book is an important addition to the library of anyone in the engine development field:

Heywood, J. B.: Internal combustion engine fundamentals. McGraw-Hill, New York, 1988.

Fuel injection and ignition systems have not been covered in this book. Robert Bosch GmbH publishes comprehensive books on both diesel and spark-ignition fuel injection systems. These books are expected to be regularly revised, and the revisions current at the time of this writing are as follows:

Bauer, H. (ed.): Gasoline engine management. Robert Bosch GmbH, Stuttgart, 1999.
Bauer, H. (ed.): Diesel engine management, 2nd ed. Robert Bosch GmbH, Stuttgart, 1999.

Engine design continues to evolve as technology and materials advance, and market and regulatory demands change. References on current practices in production engine design soon become dated, but the engine designer can maintain currency by studying the papers published each year on new engine designs. The following papers present summaries of recent engine designs at this writing:

Spark-ignition automobile engines

Shiraki, M., Moroi, Y., Tanaka, T., Tokuno, H., Nakamura, H.: Development of a new 5.6 L Nissan V8 gasoline engine. SAE 2004-01-0985, 2004.

Hill, C.M., Miller, G.D., Gardner, R.C.: 2005 Ford GT powertrain – supercharged supercar. SAE 2004-01-1252, 2004.

Otobe, Y., Kawaguchi, H., Ueshima, H.: Development of the high-power, low-emission engine for the ‘Honda S2000’. SAE 2000-01-0670, 2000.

Willenbockel, O., Schnittger, W., Subhedar, J., VanSlyke, M., Kolodziej, G.: ECOTEC – GM’s new global 4-cylinder engine. SAE 2000-01-1392, 2000.

Okuzumi, T., Amari, K., Ishihara, S., Okawa, H., Murata, K.: Development of a new high-performance Nissan V8 engine. SAE 2001-01-0329, 2001.

Regueiro, A.: DaimlerChrysler’s new 1.6L, multi-valve 4-cylinder engine series. SAE 2001-01-0330, 2001.

Rotary spark-ignition engine

Ohkubo, M., Tashima, S., Shimizu, R., Fuse, S., Ebino, H.: Developed technologies of the new rotary engine (RENESIS). SAE 2004-01-1790, 2004.

Diesel automobile engines

Abe, T., Nagahiro, K., Aoki, T., Minami, H., Kikuchi, M., Hosogai, S.: Development of new 2.2-liter turbocharged diesel engine for the EURO-IV standards. SAE 2004-01-1316, 2004.

Neumann, K., Kuhlmeyer, M., Pohle, J.: The new 1,9 L TDI diesel engine with low fuel consumption and low emission from Volkswagen and Audi. Societe des Ingenieurs de l’Automobile, Paris, France, SAE 923034, 1992.

Thoma, F., Fausten, H.: The new four-valve 6-cylinder 3.0 liter Mercedes-Benz diesel engine for the executive class passenger vehicle. SAE 932875, 1993.

Menne, R., Lawrence, P., Horrocks, R., Robertson, P.: Ford 4-valve light-duty DI diesel developments. SAE 941926, 1994.

Diesel heavy-duty engines

Suginuma, K., Muto, H., Nakagawa, H., Yahagi, T., Suzuki, T.: Hino J-series diesel engines developed for the U.S. 2004 regulations with superior fuel economy. SAE 2004-01-1314, 2004.

Altermatt, D., Croucher, S., Shah, V.: The design and development of the IVECO GENESIS diesel engine family. SAE 921699, 1992.

Hower, M., Mueller, R., Oehlerking, D., Zielke, M.: The new Navistar T 444E direct-injection turbocharged diesel engine. SAE 930269, 1993.

Okino, M., Okada, K., Abe, M.: ISUZU new 8.4L diesel engine. SAE 850258, 1985.

Sibley, J., Richards, R., Krikke, R., Forney, S.: The Caterpillar 3176 heavy duty diesel engine. SAE 881856, 1988.